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# Design and verification of an innovative handling system for electrodes in manufacturing lithium-ion battery cells

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**Abstract**

The automated handling of electrodes for manufacturing lithium-ion battery cells for automotive applications is a bottleneck of the productivity. Current handling methods are hardly efficient enough due to the usage of sequential pick-and-place operations. One possible solution for significantly increasing the productivity of handling electrodes is waiving setting and resetting movements of handling devices through the utilization of a continuous process flow. The continuous process flow is based on the continuous grasping, moving, positioning and orientating of electrodes for the provision of assembling a z-folded electrode-separator-compound for lithium-ion battery cells without setting and resetting movements. The presented design for moving, orientating and positioning electrodes is an integrant of an overall production system for assembling the electrode-separator-compound consisting out of grasping electrodes, unwinding separator and a subsequent continuous z-folding.

Subsequent to the analysis of the requirements of an automated handling of non-rigid materials and specifically electrodes, a handling system is conceptually designed, prototypically realized and its performance is verified through various test series. The handling system requires a continuous input of single sheets of electrodes, which are initially not defined in terms of their individual orientation and position as well as their orientation and position in regard to their designated layer within the electrode-separator-compound. The handling system is based on a highly dynamic tactile movement and correction mechanism using several counter-rotating rolls with direct drives and an integrated sensor architecture for the real-time registration of orientation and position. Various test series are realized in which the process requirements of a damage-free handling and the handling accuracy simultaneous to the movement are registered and evaluated.


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*Keywords:* handling, automation, battery production

## 1. Introduction

The regulatory requirements of CO2 emissions push improvements of original equipment manufacturers (OEM) to enhance their activities in the electrification of drives. Until 2021, OEM's target to reduce their CO2 emissions by 25-30%. However, this will not be possible by solely improving powertrains and reducing the road load of vehicles. It is planned to bridge this emissions-gap through electric vehicles [1]. However, the hesitation of consumers to purchase an electric vehicle is based, among others, on the range limitations, an insufficient charging network and the high costs of batteries [2]. As a key element of electric vehicles, the battery takes up around 30-40% of the value creation during the vehicle production. Within the battery, around 60-80% of value creation is accounted for in the battery cell itself [3]. The cell manufacturing and its manufacturing processes are consequently put to the test with the objective to increase productivity, decrease manufacturing errors and consequently reduce manufacturing costs.


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## 2. Manufacturing Lithium-Ion Batteries (LIB)

The international competition of energy storage technologies for the automobile industry deals with different shapes of LIB. These shapes can be divided into three main groups: cylindrical, prismatic and pouch [4], see figure 1. These groups differ in terms of outer dimensions and inner structure. However, all shapes inherit at least one galvanic cell consisting out of positive and negative electrode, a separator material to separate the electrodes in order to prevent a short circuit and an electrolyte [5].

The cell manufacturing process comprises the cutting of electrodes and separator material, the assembly of the inner structure, the so called compound, the packaging and the filling with electrolyte, the initial charging and the ageing as well as the final grading of the charged battery cell [4].

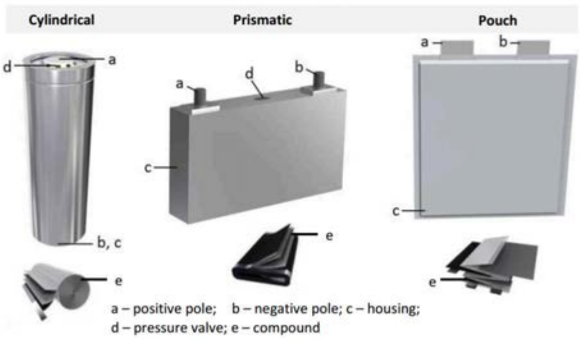


Fig. 1. Shapes of LIB and their compounds

### *2.1. Assembling the compound*

The inner structure of the LIB is characterized through the dimensions of the used materials and the process, with which the materials are processed. Whereas the cylindrical and prismatic cells use uncoiled strip electrodes and separator material to create the inner structure, the pouch cell uses single sheets of electrodes, which are stacked upon each other and physically separated by the separator [6]. Within the pouch cell, the separator can be transformed into a z-structure, in whose pockets the electrodes are placed or cut into single sheets of separator material [6, 7]. The performance for manufacturing the compounds can be compared according to the material feeding speed of the separator. Table 1 displays shows material feeding speeds for the single sheet stacking, the z-folding and the prismatic winding.

Table 1. Manufacturing performances [8, 9, 10]

| | Material feeding speed [mm/s] | Cell cycle time [s] | Performance [cpm] |
|---|---|---|---|
| Single sheet stacking | 83 | 120 | 0.5 |
| Z-folding | 129-132 | 81-83 | 0.72-0,74 |
| Prismatic winding | 300-360 | 30-36 | 1,7-2 |

The cell cycle time and the performance in cells per minute (cpm) is in reference to a 50Ah pouch cell for a Battery Electric Vehicle (BEV) [11] and the assumption of 15 cathodes, 16 anodes and a total length of a pre-processed separator of around 10m.

### *2.2. Challenges and objectives*

The performance gap between the stacking and z-folding with the prismatic winding is constituted in the underlying procedure. The winding procedure is virtually continuous since the compound is manufactured through a single sequence of acceleration, upholding and the deceleration of the winding spindle rotation. The z-folding and stacking procedure require various sequential sequences for grasping, moving and placing electrodes to the joining site of where the compound is assembled [12]. The procedure is therefore discontinuous and the average material feeding speed for manufacturing an electrode-separator-compound is significantly lower than it is for the continuous winding procedure. This is one of the reasons, the manufacturing of the z-folded and the stacked compound is the bottleneck of the cell manufacturing [13].

Because of the various sequential handling tasks, the currently available machinery for manufacturing the compound is considered to be inefficient and therefore jointly responsible for increasing the manufacturing costs [14]. Reducing the manufacturing costs involves quality procedures in order to reduce manufacturing errors [15], less expensive raw materials and consequently a significant increase in the performance of current manufacturing processes [13, 16]. The current state of the art concerning the performances for manufacturing the z-folded structure, see table 1, calculates to a sheet cycle time of 2,5s/electrode.

However, increasing the cycle time of handling an electrode using industrial robots implies an increased and more rapid acceleration and deceleration of the heavy robot arms. This entitles the risk, that the surface-sensitive and non-rigid electrodes are being deformed and/or damaged [17]. Furthermore, the current handling solutions rely on a complex verifying and alignment procedure using camera systems in order to ensure a precise position and orientation of the electrodes. These procedures are most precise, if the object is steady in its state or traveling at low velocities only. Altogether, the conflict of objectives is the achievement of a fast verifying and alignment procedure, a low sheet cycle time and a damage-free handling of electrodes.

The German Engineering Association (VDMA), one of the largest industrial associations in Europe consequently defines the increase in productivity at manufacturing the compound as one strategic “red-brick-wall”. This wall is to be broken down by the development of innovative handling solutions, which avoid sequential handling operations [13] and are able to achieve a sheet cycle time of below 1s.

## 3. Design of the handling system

Changing the procedure for manufacturing the compound from sequential to continuous has already been identified by industry as being a promising option for increasing productivity [18, 19]. A conceptual development of a handling system prospectively being able to significantly increase productivity has been presented in [20]. In order to establish a fully automated handling system, a robust technical design is established and the prototype is subsequently verified through various test series.

### 3.1. Requirements

The concept is based upon a tactile movement mechanism using several counter-rotating rolls. Besides moving the electrodes at a minimum material feeding speed of 500mm/s, a correction movement of position and orientation has to be carried out simultaneously in order to establish a continuous process flow. The verifying and alignment procedure has to be integrated in the handling process and has to function while the electrode is in full material feeding speed. The position and orientation errors of electrodes exiting the handling system shall not exceed ±0,1mm [21]. In addition, and likely most important, the movement and the corrective motions at an average material feeding speed of 500mm/s are to be carried out without damaging or deforming the surface-sensitive and electrode.

### 3.2. Input and output constraints

The input constraints for electrodes entering the handling system with a defined velocity $\overrightarrow{v_E}$ are an undefined

- orientation around the z-axis of $\Delta\phi$= within ± 6°
- position in x-axial direction of $\Delta x$= within ±50mm and
- position in y-axial direction of $\Delta y$= within ±7mm, see figure 2.

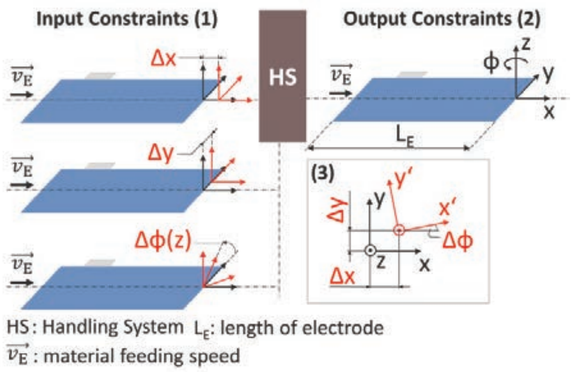

Fig.2. Constraints for electrodes entering (1) and exiting (2) the handling system. Possible combination of input constraints (3), displayed as a transformed coordinate system (red vs. black)

The rotational degrees of freedom around the y- and around the x-axis are constrained due to physical limitations of the handling system and are nonessential for consideration. Further, the mentioned input constraints will not occur singular and the handling system will be required to cope with a variety of constraint-combinations. The output constraints are congruent with industrial standards [24] and are a defined

- orientation around the z-axis of $\Delta\phi$= ± arctan(0,1mm/$L_E$)
- position in x-axial direction of $\Delta x$= ± 0,1mm and
- position in y-axial direction of $\Delta y$= ± 0,1mm.

The output constraints are defined in relation to the placement accuracy required in the assembly of the compound. Irrespective of the fact, that anodes are slightly larger than cathodes and the intermediate separator layers are larger than the anodes [22], the output constraints are to be met every folding length $L_f$, see figure 3.

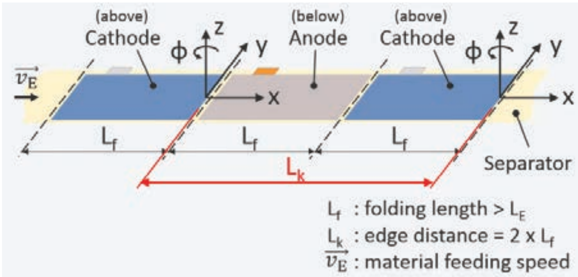

Fig. 3. Meeting the output constraints

### 3.3. Design and setup

The concept consists out of four serial handling devices, which are positioned equidistant to one another and are bordered by an ultrasonic bearing, see figure 4.

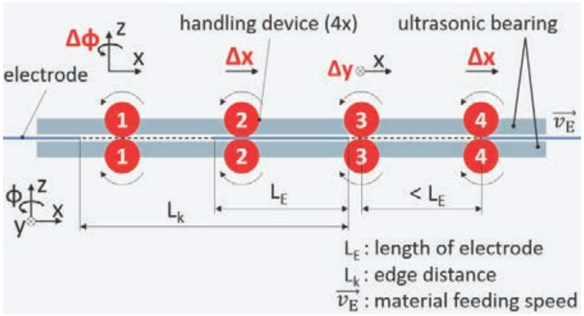

Fig. 4. Concept functionality and correction modes of the handling devices

A handling system is designed to move, orientate and position either anodes or cathodes. Two handling systems are required to handle anodes and cathodes path-synchronous.
The ultrasonic bearing comprises sonotrodes, which are designed in a sandwich-structure in order to limit the degrees of freedom of the electrode along the z-axis during handling. An entering electrode is guided into an approximate gap of 0,5mm between the opposing sonotrodes due to their convex design and received by the first handling device. Each handling device comprises two opposing pairs of counter-rotating rolls.
Figure 5 shows the setup of the prototype for handling electrodes. The top left depicts the entrance to the handling system with a wide convex opening of the sonotrodes as well as a single sensor as part of a broader sensor architecture. The top right shows the exit as well as a rear view of the fourth handling device, see figure 4.

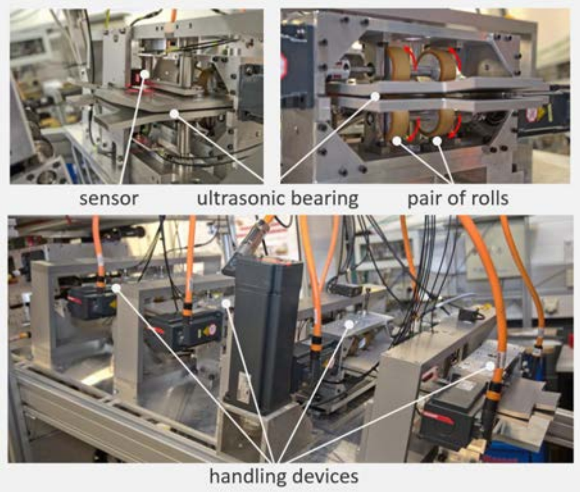

Fig. 5. Entrance (t. l.) and exit (t. r.) and setup (bottom) of handling system

The arrangement of the handling devices depicted in figure 4 is constituted by the corrective motion sequences for Δx, Δy and Δϕ and explained following.

*3.4. Corrective motion sequences*

The handling devices have the task to move the electrode and to execute a corrective motion sequence in order to meet specific output constraints if necessary. The information required is collected through photo sensors, detecting the presence of an object and through laser sensors, which have a specific measuring range in order to detect displacements of the passing electrode. Each handling device relies on information provided by a set of sensors. The sensors detect the position and orientation of the electrode, the required compensation is calculated by the programmable logic controller by comparing the actual state of the electrode, i.e. the gravity of input constraints and their combination, with the target state, i.e. the output constraints.

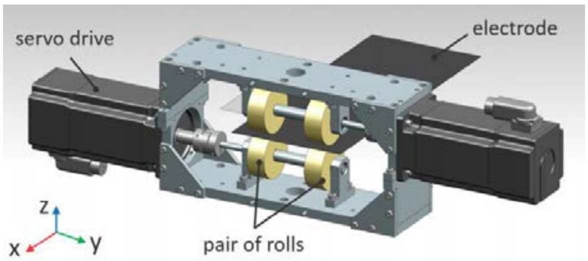

Fig. 6. Handling device

According to the input constraints, three different corrective motion sequences are implemented within the logic controller of the handling system.

- Δx is a position error along the direction of motion (x-axis). The compensation is realized through the selective acceleration and deceleration of the counter-rotating rolls of a handling device superimposed to the movement of the electrode.
- Δy is a position error transversal to the direction of motion (y-axis). The compensation is realized through a crankshaft movement, shifting a single handling device within the handling system transversally superimposed to the constant movement of the electrode.
- Δϕ is an orientation error around the z-axis. The compensation is realized through a crankshaft movement rotating a single handling device within the handling system, using the center of gravity between the pair of rolls as a rotational axis. The correction is superimposed to the constant movement of the electrode.

The actuation point of the handling device lies in between a pair of opposing counter-rotating rolls. Two pair of opposing counter-rotating rolls result in two actuation points of one handling device. The actuation points of one handling device are in line with one another. The distance of the actuation points of two handling devices is slightly less than the length of an electrode, see figure 4. The distance deviation from the handling devices to one electrode length results in a rigid material transfer from one handling device to the next one. This system characteristic is reasoned in upholding the executed position and orientation corrections. However, this rigid material transfer implies that at specific point in time, two handling devices are simultaneously handling one electrode. To avoid deformation or surface-damage to the electrode, no corrective motion sequences are to be executed or still being executed while one electrode is being handled simultaneously by two handling devices. This length of simultaneous contact is following defined as $L_C$. Furthermore, the material feeding speed of the two handling devices simultaneously handling the electrode need to be identical.

The execution of the corrective motion sequences constitutes the arrangement of the handling devices in figure 4. The orientation offset Δϕ is detected at the beginning of the handling system. The first handling system is pre-orientated to the detected offset and reset to Δϕ=0 while the electrode is being moved at a constant velocity. However, the reset orientation has to be reached before the moving electrode arrives at the actuation points of the subsequent handling device in order to not be deformed. The corrective motion of the subsequent handling device relies on preceding registered sensor data. The counter-rotating rolls are able to execute a movement-superimposed correction along the direction of motion by accelerating or decelerating. The subsequent handling device three is designed to compensate errors along the y-axis. This error can be caused by preceding processes, e.g. the separating and accelerating of the electrodes. In addition to preceding processes, a Δy-error can be cause by an executed Δϕ-correction. Since the handling device for executing a Δϕ-correction is pre-orientated, a temporary diagonal movement occurs until the corrective motion sequence of Δϕ has been executed. The fourth handling device is identical to the second one and is executing a Δx-correction, if an x-offset is still registered at this point. If no position offset is registered, the handling devices will move the electrode at the constant material feeding speed $\overrightarrow{v_E}$.

## 4. Verification

In order to develop a competitive highly automated handling process for electrodes, the designed handling system needs to be verified for an accurate and damage-free handling process.

### 4.1. Corrective motion accuracy

The drives of the handling system are dimensioned for a design point of $\overrightarrow{v_E}$ = 500mm/s. Simultaneous to $\overrightarrow{v_E}$, the drives need to manage displacement corrections in the range of Δx= ± 50mm, Δy = ± 7mm and/or Δϕ= ± 6°. The required dynamics of the drives are a function of the time frame available for the corrective motion $t_{CM}$. The available time frame calculates from the total time of contact $t_T = L_E/v_E$ between the actuation points of the handling device and the electrode, minus the amount of time $t_C$ resulting from the length $L_C$ of the simultaneous contact of two handling devices, resulting in $t_{CM} = t_T - t_C$. $L_C$ is set to 0,05m at the beginning and at the end of the electrode, $t_C = L_C/v_E$. Assuming $L_E$=$L_C$=const., $t_{CM}$ increases with a decrease of $\overrightarrow{v_E}$. An increase of $t_{CM}$ results in further dynamic requirement to be met by the drives of the handling system.

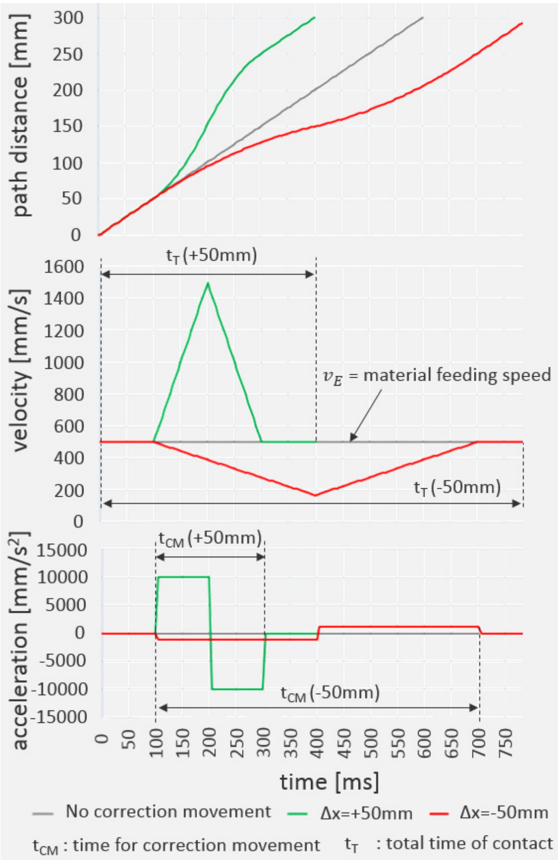


Fig. 7: Correction movement for Δx= ± 50mm for $v_E$=0,5m/s and

Figure 7 shows an actual Δx-correction movements for ±50mm and a velocity of 500mm/s. The green graph displays a correction movement of Δx=+50mm. The total time of contact for an electrode of $L_E$ = 300mm equals to $t_T$ = 0,4s and the time frame available for correction is $t_{CM}$ = 0,2s, since $t_C$ = 2 x 0,1s = 0,2s. The selected servo drives provide a rated torque of 2.30Nm with a rated speed of 3000min$^{-1}$ and a rated power of 0,72kW.

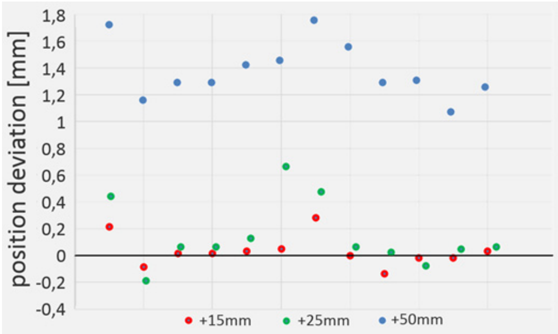


Fig. 8: Accuracy of the Δx-correction (15mm; 25mm; 50mm)

Several test series were performed to verify the correction movements and their accuracy. Figure 8 shows the position accuracy of Δx [+50mm; +25mm; +15mm]. Further, a Δy-correction of ±7mm has been realized through various test series and verified in its accuracy for a material feeding speed of 500mm/s according to figure 9. The reachable repeatability – target position 0 - during the positioning of the electrode runs below the allowed tolerance by approximately factor 5.

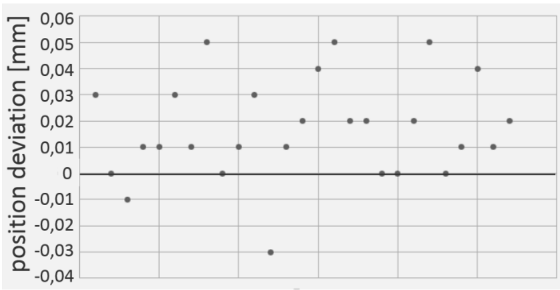


Fig. 9: Accuracy of the Δy-correction (±7mm)

Compensating an orientation error Δϕ around the z-axis through the crankshaft movement has not been fully verified yet. However, initial test series have already shown a promising dynamic and accuracy of the correction movement.

### 4.2. Damage-free handling

The roll-material used to realize correction movements is a polyester-urethane rubber (AU according to ISO 1629) which shows the properties of a high mechanical and chemical stability. Figure 10 displays macroscopic and microscopic surface characteristic before and after optimizing the handling process.

The macroscopic examination displayed distinctive surface transport marks, which were reason to an excessive normal force of the actuation points. The stress limit of the surface sensitive coating material was exceeded which led to compression, see figure 10, a. The microscopic influence of exceeding the stress limit during handling is displayed in figure 10, c. However, the displayed accuracies of the correction movements, figure 8 and figure 9, were realized without damaging the surface, see figure 10, b and d.

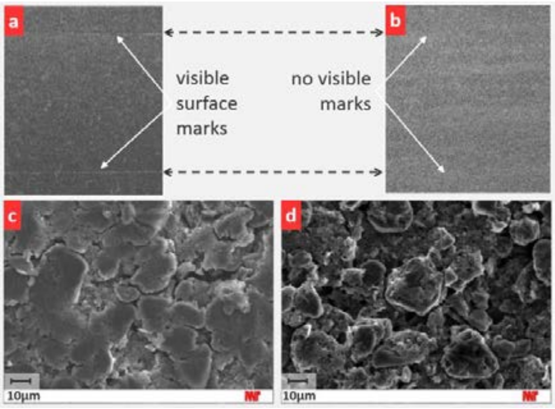


Fig. 10: Macroscopic (a, b) and microscopic (c, d) surface quality before (a, c) and after (b, d) improving the handling process

## 5. Conclusion and outlook

The development of an innovative handling solution for electrodes is an important step towards efficiently manufacturing LIB. Current manufacturing processes for assembling the electrode-separator-compound rely on sequential pick-and-place operations, which are limited in their possible dynamics by the inertial mass of the robot arms and the actuators. A possible solution for increasing productivity in handling electrodes is the utilization of a continuous process flow. The continuity is characterized by the continuous provision of orientated and positioned electrodes and the constant material feeding speed of the separator. Without generating secondary processing time through resetting movements of handling devices, the introduced process is able increase the productivity. Within this paper, a handling system for the tactile movement and the dynamic position and orientation of surface-sensitive and non-rigid electrodes has been introduced and prototypically realized. Various test series verified the position accuracy and the ability for executing a damage-free handling for a constant material feeding speed of $\overrightarrow{v_E}$ = 500mm/s, displaying an increase in productivity of more than 240% compared the current state of the art in handling large-scale electrodes within the z-folding process.

Future work focuses on increasing $\overrightarrow{v_E}$ while maintaining or improving the position and orientation accuracy. Additionally, novel electrode materials need to be tested in order to estimate the impact, efforts and investments to the handling system. Furthermore, the handling system is to be integrated into a fully automated assembly process for manufacturing of z-folded LIB. Preceding process steps are the continuous grasping and separating electrodes from a stack and subsequent process steps are the jointing of electrodes to the moving separator as well as the continuous z-folding of separator material, e.g. [23]. The assembly of the compound is preceded by separating the electrodes using e.g. laser-cutting and succeeded by packaging the z-folded compound into a housing.

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## References

[1] Bernhart, W., Schlick, T.: Automotive Lithium-Ion Batteries – Status and Outlook. Roland Berger Strategy Consultants. In: Kraftwerk Batterie – Lösung für Automobil und Energieversorgung. Aachen, p. 2ff., 2015.
[2] Hoffmann, P.: Hybridfahrzeuge. Heidelberg, Springer-Verlag, 2010.
[3] N.N.: Forschung zu Batteriefertigung – BMBF Startet Forschung zu Lithium-Ionen Zellen. In: Pressemitteilung 082/2015, 15.06.2015.
[4] Kampker, A.; Valée, D.; Schnettler, A.: Elektromobilität. Grundlagen einer Zukunftstechnologie. Springer Vieweg, pp. 203, 2013.
[5] Beermann, M. et al.: Quo Vadis Elektroauto? Grundlagen einer Road Map für die Einführung von Elektro-Fahrzeugen in Österreich. Bundesministerium für Verkehr, Innovation und Technik, Graz, 2010.
[6] Reinhart, G.; Kurfer, J.: Handhaben in der Batteriefertigung. In: wt-online, Vol. 9, pp. 545-550, 2011.
[7] Kampker, A.; Deutskens, C.; Heimes, H.; Nowacki, C.; Maiser, E.; Michaelis, S.: Der Produktionsprozess einer Lithium-Ionen Folienzelle. RWTH Aachen, WZL und VDMA, Aachen, 2012.
[8] GEESUN Automation Technology: Products. China, 2014. Information on: www.geesun.com/en/product_show.asp?id=11. [25/3/15]
[9] HI-MECHA CORPORATION: Electrode Stacking Machine. Hi-Mecha Company Inc., Japan, 2014. Information on: www.hi-mecha.co.jp/english/denseki.html. [15/5/15]
[10] Wuxi Lead Intelligent Equipment Co. Ltd.:. LVEV 400EV Winding Machine. Information on: www.leadchina.cn/en/cp02-04.htm. [13/2/16]
[11] DIN SPEC 91252:2011-01 (D): Elektrische Straßenfahrzeuge - Batteriesysteme – Abmessungen für Lithium-Ionen-Zellen, p. 7, 2011.
[12] Zäh, M.F., Schmitz, P., Westermeier, M.: Produktionsforschung für den elektrischen Antriebsstrang. In: Produktionskongress 2014, München, pp. 98-110, 2014.
[13] Maiser, E.; Michaelis, S.; Müller, D.; Kampker, A. et al.: Roadmap Batterie-Produktionsmittel 2030. Hrsg.: VDMA Batterieproduktion, Frankfurt am Main, Deutschland. 06.10.2014.
[14] Baumeister, M.; Fleischer, J.: Integrated cut and place module for high productive manufacturing of lihtium-ion cells. In: CIRP Annals – Manufacturing Technologie 63, pp. 5-8, 2014.
[15] Kölmel, A.; Sauer, A.; Lanza, G.: Quality-oriented production planning of battery assembly systems for electric mobility. In: 5th Conference on Assembly Technologies and Systems, 2014.
[16] Heinrichs, M.; Trechow, P.: Lithium-Ionen Speicher: Teuer, sensibel und talentiert. In: VDI nachrichten, 30. Januar 2015, Nr. 5, p. 17, 2015.
[17] Fleischer, J.; Ruprecht, E.; Baumeister, M.; Haag, S.: Automated Handling for Limp Foils in Lithium-Ion-Cell Manufacturing. In: 19th CIRP International Conference on Life Cycle Engineering, Berkley, 2012.
[18] Bidian, P.; Pfister, U.; Steinmetz, H.: Method for manufacturing electrode stack for battery i.e. lithium-ion battery. Patented by the Daimler AG, DE102010055617A1, publishing date 28.06.2012.
[19] Bidian, P.: Produktionstechnologien für Li-Ionen Fahrzeugbatterie-systeme. In: VDI-Fachkonferenz Batterieproduktion und Recycling, Stuttgart, p. 12. 14.11.2012.
[20] Aydemir, M.; Bach, G.; Schröder, R.; Glodde, A.; Seliger, G.: Handhaben von Elektrodenfolien. In: wt online, Jg. 105, H. 9, pp. 591-596, 2015.
[21] Kampker, A.; Heimes, H.; Deutskens, C.; Ordung, M.; Maiser, E.; Michaelis, S.: Produktionsprozess einer Lithium-Ionen-Batteriezelle. In: RWTH Aachen and VDMA Batterieproduktion, 2nd Edition, Aachen, Frankfurt, p. 11, October 2015.
[22] Hohenthanner, C.-.R.; Mecklenburg, A.: Produktionsforschung für Hochleistungs-Lithium Batterien. In: 10. Karlsruher Arbeitsgespräche Produktionsforschung. p. 112, 2010.
[23] Schröder, R.; Glodde, A.; Aydemir, M.; Bach, G.: Process to Increase the Output of Z-Folded Separators for the Manufacturing of Lithium-Ion Batteries. In: Applied Mechanics and Materials, Vol. 794, pp. 19-26, 2015.